

# THE EFFECT OF MOISTURE CONTENT ON DETERMINING CORN HARDNESS FROM GRINDING TIME, GRINDING ENERGY, AND NEAR-INFRARED SPECTROSCOPY

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**ABSTRACT.** *The Stenvert hardness test was used to determine the energy-to-grind (ETG) and time-to-grind (TTG) of 107 food-grade corn hybrids at different moisture content (MC) levels. ETG and TTG were significantly affected by moisture content. Across hybrids, ETG displayed the most consistent response between 10% and 13% MC wet basis. An equation was developed to adjust ETG and TTG to a common MC level in order to minimize moisture effects on corn-hardness determination. ETG was considered to be the preferable method to measure corn hardness, considering ETG adjustments, based on MC, were more accurate using the developed equation. Results also supported grinding at MC levels between 10% and 13% MC to obtain the most accurate results, as opposed to higher MC levels. Grinder speed effects were also found to be significant but controllable, and the repeatability of ETG and TTG were about the same. Near-infrared reflectance spectroscopy was concurrently evaluated as a method to measure corn hardness in terms of ETG and TTG on whole-kernel and ground material from the grinder. Predictive models were poor using spectra (500 to 1700 nm) of whole-kernel and ground samples. Moisture-correction methods developed in this work allowed samples of corn to be tested over a broader range of MC. This provided more convenience and greater confidence in grinding parameters as a measurement of corn hardness.*

**Keywords.** *Corn, Hardness, Grinding, Quality.*

The purpose of hardness measurement in food grade corn is to quantify its value for certain processes and products. Hardness is a somewhat ambiguous term but is often used to reflect the ratio of hard (corneous or vitreous) to soft (starchy) endosperm. A high ratio of hard endosperm is desirable in dry milling to produce large flaking grits, which are most profitable, and processors include hardness in evaluating corn quality. Hardness measurement is important in breeding in order to retain trait characteristics (Pratt et al., 1995). Several methods for hardness measurement have been investigated and are in use, but none provide a complete solution. These methods include visual measurement of endosperm ratios (Kirleis et al., 1984), density or test weight, true kernel density, percent floaters, particle-size index of ground material, grinding time, and energy and ground material properties. It is generally agreed that, prior to hardness measurements, corn samples should be equilibrated to a common moisture content or a correction factor should be applied (Paulsen

et al., 2003). For processors, equilibrating to a common MC may not be feasible and methods to correct for moisture are desired.

Early work by Tran et al. (1981) used a Strong-Scott barley pearler to determine corn abrasion resistance and hardness. Grinding energy was found to be linearly related to moisture content (MC) and decreased with increasing moisture. Similarly, a tangential abrasive de-hulling device, used by Lawton and Faubion (1989), was affected by moisture content. Both of these methods tend to measure hardness of only the outer layer of the kernel. Hardness measurement of wheat using the Perten SKCS 4100, single-kernel characterization system corrects for moisture content indicating the need to adjust hardness values for moisture (Martin et al., 1993). Color segmentation of kernel endosperm employing machine vision was used by Liao et al. (1991) to classify hardness. In general, good agreement was obtained between human visual classification of hardness and machine vision.

Pomeranz et al. (1984) evaluated physical and chemical properties of three corn hybrids in relation to their kernel shape and shape characteristics. Properties were compared to corn hardness measured by the Stenvert hardness test (SHT) (Stenvert, 1974). The three SHT parameters used were the time to grind a 20-g sample, and the volumetric and weight ratios of the hard and soft endosperm. Hard and soft endosperm types separate during grinding. Near-infrared absorbance at 1680 nm was also examined and was found to have some correlation ( $r = 0.55$  to  $0.68$ ) with SHT parameters. Moisture content was measured but not reported on samples, and its effect on grinding was not discussed. Robutti (1995) used near-infrared transmittance (NIT) to determine hardness class of corn hybrids. Absorbance at 860 nm was found to segregate classes reasonably well.

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Dorsey-Redding et al. (1990) determined MC effects on SHT measurements. Column height of ground material was the only parameter reported from the SHT measurements because of bridging problems at high MC levels. A linear model equation was developed to correct column height for MC. Li et al. (1996) found total grinding energy of 38 corn hybrids, using the SHT, correlated well with grinding time ( $r = 0.79$ ) and the ratio of hard to soft endosperm ( $r = 0.74$ ). Wet-basis moisture content of the samples ranged from 9.6% to 12.4%, with the majority ranging from 10% to 11%.

The effect of moisture content on the SHT parameters has not been investigated thoroughly for the SHT. Ideally, a hardness test should yield a value that reflects useful properties that are immune from other kernel conditions, and is easy and quick to use. The objectives of this study were to quantify the effects of MC on the SHT parameters of grinding time (TTG, time-to-grind) and energy (ETG, energy-to-grind), and provide parameter adjustments equilibrated to a common MC. Grinding energy is appealing as a measurement because it can be totally instrumented and is less subjective than other parameters from the SHT. Near-infrared reflectance (NIR) spectroscopy was also performed on samples of whole-kernel and ground material from the grinder to determine if NIR can be used to predict SHT parameters.

## MATERIALS AND METHODS

### GRINDING PROCEDURES

All grinding was done on 20-g samples using a Glenn Mills micro-hammer cutter mill. (Glenn Mills Inc, Clifton, N.J.). The 20-g samples were weighed just prior to grinding. The initial mill speed was adjusted to 3600 rpm prior to grinding except for tests specifically examining grinding speed effects. Speed was set using the mill speed controller and a tachometer measuring shaft speed. Corn samples were placed in the mill hopper and the entire sample was then released into the grinding mechanism. The time to accumulate 17 ml of ground corn into the receiving vial was recorded as TTG. ETG was determined by measuring grinder motor current. A sensing mechanism to measure instantaneous current was built specifically for the mill by passing one AC conductor powering the mill through a small single-winding coil (AC1005, Telema Electronic LLC, Rolla, Mo.). Coil output was connected in parallel to a 1k-ohm resistor to provide a sensing voltage that was later equated to motor current. The sensing voltage was digitized at 300 Hz by a USB data acquisition unit (PMD1112, Measurement Computing, Norton, Mass.). A custom program was written to record and display data. The rise in the sensing voltage at the beginning of grinding triggered recording. Grinding was stopped after 40 s. RMS sensing voltage values were calculated and stored to a file. Voltage data was then integrated over the 40-s period and converted to total energy. The energy required to run the mill with no load was determined and subtracted from the total energy to obtain ETG. The unloaded grinder current was monitored prior to grinding and remained constant over all testing. After grinding, samples were placed in sealed plastic bags and refrigerated, at 4.5°C, awaiting NIR spectral measurements. A 40-s grinding period allowed most of the kernel material to pass through the grinder, with a small portion of the

corneous endosperm remaining in the grinder housing. It is noted that the 3600-rpm speed was the initial speed and that the grinder slows as the grinding load increases and then increases as the load decreases toward the end of the test.

### GRINDING SPEED

Tests were completed to determine the effect of grinder speed on ETG and TTG. Four commercial-food-grade, yellow-dent hybrids were equilibrated to a constant MC of approximately 13% (average = 12.93, std. dev. = 0.19) in an environmental chamber for two weeks. All reported MCs are on a wet basis. Three sub-samples of each hybrid were then ground at 3500, 3600, and 3700 rpm using the grinding procedure described. Each test condition was done in triplicate.

### GRINDING REPEATABILITY

Three hybrids representing a range of hardness (hard, medium, soft) based on TTG values were selected to determine repeatability of measurements and an initial analysis of the effect of MC on ETG and TTG. All samples were yellow-dent hybrids. Samples were conditioned to three moisture levels of approximately 12.5%, 13%, and 14.5% MC. An initial oven-dried MC was determined for each sample (*ASABE Standards*, 2006). Distilled water was added to the sample, or the sample was dried at 35°C to obtain the correct MC. Half of the water was initially added and the remaining added seven days later. Samples were kept in a cooler at 10°C during this time. Dried samples were monitored for weight to determine when they were at the correct MC. All samples were stored another 10 days in the cooler prior to tests. Three replicate sub-samples from each hybrid at each MC were ground to determine ETG and TTG. True sample MC was then determined by oven drying of sub-samples.

### MOISTURE EFFECTS

ETG and TTG were measured for 107 commercial-grade food hybrids at three MC levels. Near-infrared reflectance (NIR) spectral measurements were collected on whole-kernel corn prior to grinding and then after grinding on the ground material collected in the receiving vial. Specific procedures are discussed below.

Samples of approximately 120 grams were obtained from corn hybrid trial plots administered by Kansas State University. Thirty-gram samples for each hybrid were placed into small parts cabinets and then placed into an environmental chamber to condition samples to a specific moisture level. Temperature and relative humidity in the environmental chamber were maintained to within  $\pm 0.5^\circ\text{C}$  and  $\pm 2\%$  RH, respectively. Samples remained in the environmental chamber for a minimum of 10 days before grinding tests and NIR measurements. This procedure was repeated for three different MC levels. Equilibrium moisture content (EMC) environmental parameters for MC conditioning are shown in table 1, along with MC statistics obtained from oven drying (*ASAE Standards*, S352.2) after conditioning. Grinding procedures were performed on each hybrid as previously described. Ground material that passed through the grinder was placed in a sealed plastic packet and stored at 10°C for spectral measurements.

**Table 1. Moisture contents statistics and equilibrium moisture conditions for the 107 hybrid samples.**

	MC Statistics (%MC)		Conditioning Parameters	
	Average	Std Dev.	Temperature (°C)	Relative Humidity (%RH)
Low MC	9.25	0.29	15	32
Med MC	13.92	0.42	15	68
High MC	15.41	0.35	15	75

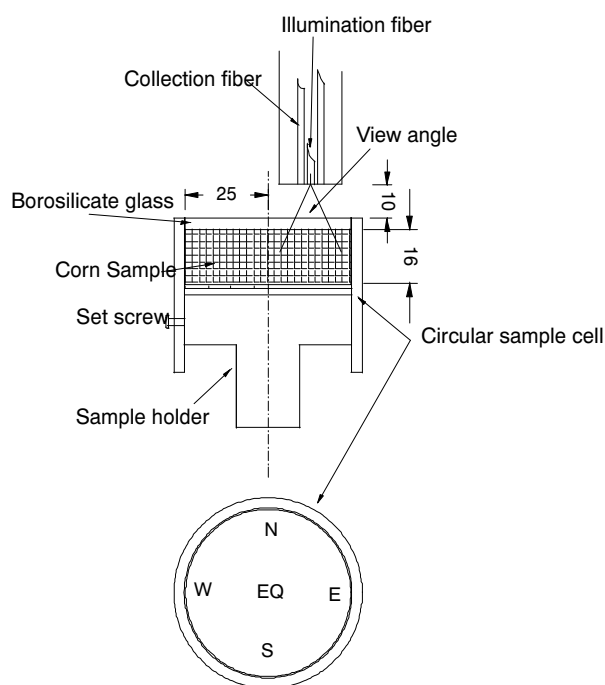
## NIR HARDNESS MEASUREMENTS

Spectra (400-1700 nm) of whole-kernel and ground-kernel samples were obtained from the spectrometer (DA 7000, Perten Instruments Inc, Springfield, Ill.) in reflectance mode using the sample holder and fiber-optic probe shown in figure 1. Material was placed in the inverted, circular sample cell and gently tapped a few times to settle material. Sample depth was approximately 16 mm. The sample holder was inserted into the cell and the set screw tightened. Four spectra were collected at each position, EQ, N, S, E, and W for a total of 20 spectra per sample; each spectrum was the average of 15 spectra. Positioning of the sample holder was done by hand. Whole-kernel spectra were taken on the sample to be ground. After whole-kernel spectra collection, samples were returned to the environmental chamber to remain conditioned to the correct MC for grinding. Samples of ground material were thoroughly mixed prior to spectral measurements by placing material into a small, baffled tube and shaken for 20 s.

## RESULTS AND DISCUSSION

### GRINDING SPEED

Results from varying grinding speeds showed ETG and TTG values were different for each hybrid at speeds of 3500,



**Figure 1. Sample cell used to collect NIR spectra (dimensions are in mm).**

3600, and 3700 rpm. ETG and TTG were also different between hybrids. Two hybrids had much higher ETG and TTG values at a fixed speed than the other two, indicating differences in hardness. Figure 2 shows the normalized value of ETG and TTG for each hybrid for easier comparisons, i.e., individual ETG and TTG were divided by the average for all speeds for each hybrid. TTG decreases in an approximate linear manner with increasing grinding speed. The decrease would seem logical since it should take less time to grind a fixed volume at higher speeds. The behavior of ETG was seen to increase with speed but was less influenced by speed compared to TTG. Small fluctuations in initial grinding speed,  $\pm 10$  rpm, should not affect ETG or TTG values significantly. Speed differences of this magnitude are relatively easy to control and thus should not present a problem in obtaining repeatable results.

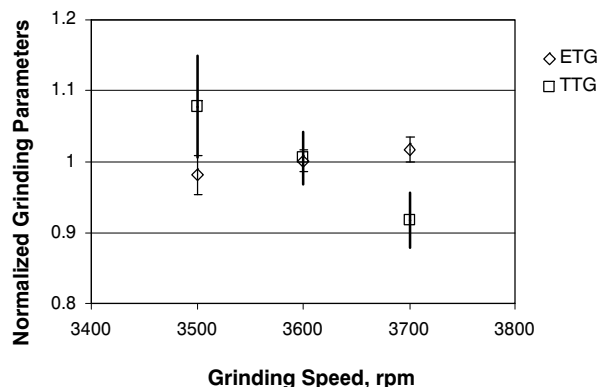
### GRINDING REPEATABILITY

The coefficient of variation (cv) from replicate measurements of ETG and TTG (table 2) shows that ETG and TTG are equally repeatable. The coefficient of variation was calculated as the standard deviation calculated from the three replicate measurements divided by their average and multiplied by 100. The standard deviation of individual samples for ETG ranged from 9 to 206 joules; the range for TTG was 0.02 to 1.63 s. Average standard deviation of all samples was 63 joules and 0.70 s for ETG and TTG, respectively. The curves showing instantaneous grinder power (fig. 3) indicate the typical response of grinding hybrids with different hardness. Energy is derived by numerically integrating these curves.

Effects of MC on grinding parameters show an increasing rate for both ETG and TTG with MC (fig. 4). The hybrid with low hardness was influenced more by MC than the hybrids with greater hardness. In all cases, MC had a significant effect when comparing hybrids for hardness and justifies methods to adjust hardness for MC when samples cannot be equilibrated to the same moisture level.

### EFFECTS OF MOISTURE CONTENT ON GRINDING ENERGY AND TIME

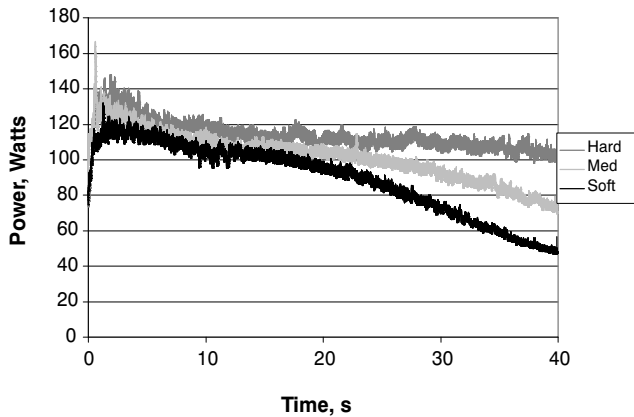
Prior to data analysis, ETG and TTG values were adjusted from measured MCs to three common MC levels for all 107 hybrids to simplify analysis. This was done by visual interpolation of graphs of MC versus ETG and TTG for



**Figure 2. Effect of grinder speed on grinding parameters, Average ETG and TTG, for four corn hybrids with standard deviation bars. Values are normalized using individual averages for each hybrid.**

**Table 2. Coefficient of variation (cv) from replicated measurement of ETG and TTG.**

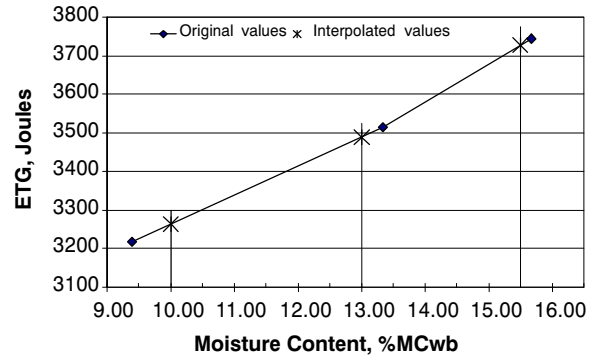
Sample	High Hardness Corn			Medium Hardness Corn			Low Hardness Corn			Avg. cv (%)
MC	14.81	12.37	9.84	14.86	12.47	9.98	15.34	12.73	10.88	
ETG cv (%)	2.5	1.08	0.38	1.04	0.74	4.73	1.17	1.01	0.47	1.45
TTG cv (%)	2.92	1.61	2.99	1.71	1.31	1.35	1.25	0.56	0.13	1.53



**Figure 3. Grinding power for three hybrids of different hardness.**

individual hybrids. The method of interpolation is shown in figure 5. Parameters were adjusted to 10%, 13%, and 15.5% MC.

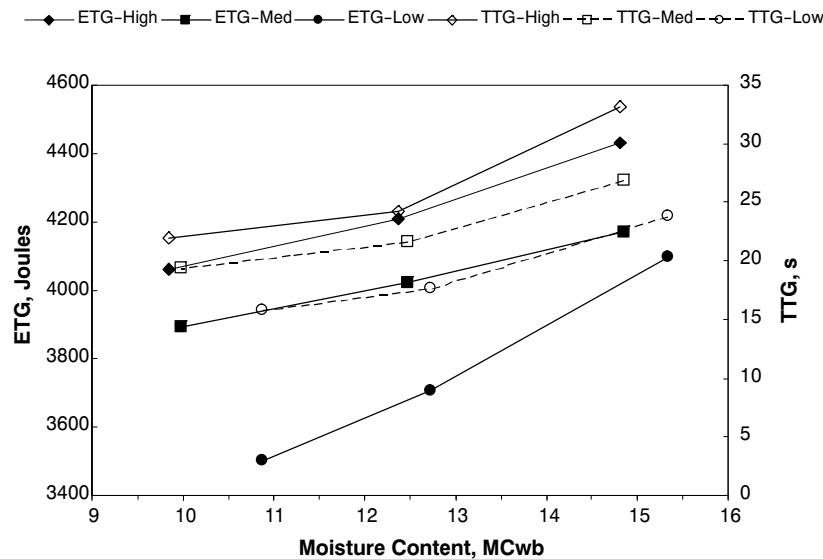
The characteristic response of interpolated ETG and TTG to MC varied and is represented by the plots in figures 6 and 7. These show either an increasing, linear, or decreasing rate change of ETG and TTG with MC. An increasing rate change for ETG and TTG versus MC was observed for approximately 59% and 55% of the hybrids, respectively. Remaining curves were nearly equally divided between linear and decreasing rates changes. For all cases, ETG and TTG increased with increasing MC. Average characteristics were examined by averaging ETG and TTG values for all hybrids at each MC level. This is also shown in figures 6 and 7. Quadratic functions were fit to all characteristic types.



**Figure 5. Method of interpolation to adjust all hybrids grinding parameters to common moisture levels of 10%, 13%, and 15.5% MC.**

Other models, such as linear models, could be applied but do not fit the data as well and are less general, i.e. they fit the linear characteristics well but not increasing and decreasing rates of the grinding parameters.

Characteristic curves were examined to determine if similarity of curves was greater between the 10% to 13% MC range when compared to the 13% to 15.5% MC for all hybrids. Slopes of the curves of these two MC intervals were calculated for individual hybrids, assuming a linear response between the two moisture points. Table 3 shows the coefficient of variation (cv) of the slope values for ETG and TTG data. These values show that ETG exhibited the most consistent characteristic pattern between 10% to 13% MC by the lower slope cv. TTG data was the least consistent. The implication is that, between hybrids, there is less predictable behavior for TTG data; the most predictable is for ETG data between 10% to 13% MC.



**Figure 4. Effect of moisture content on grinding parameters ETG and TTG. High, medium, and low refer to corn hybrids that had high, medium, and low hardness.**

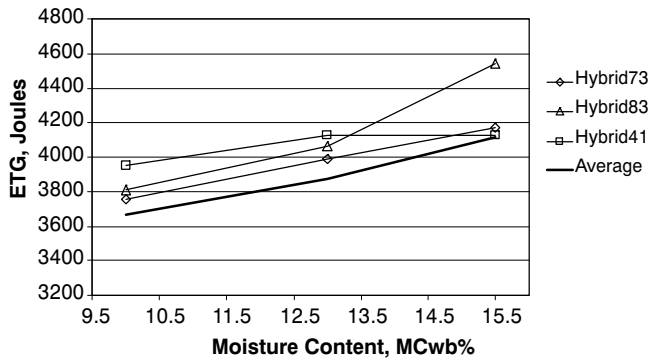


Figure 6. Different characteristic responses of ETG to MC and the average response for all hybrids.

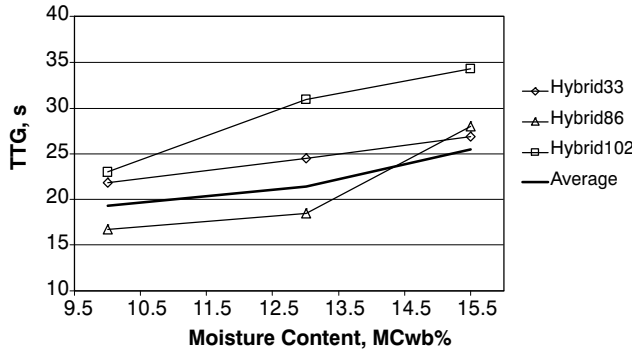


Figure 7. Different characteristic responses of TTG to MC and the average response for all hybrids.

#### CORRECTION OF GRINDING ENERGY AND TIME FOR MOISTURE CONTENT

A quadratic adjustment equation (eq. 1) was evaluated for both parameters using the average grinding parameter values at each MC. Regression of the average values yielded equations with the coefficients shown in table 4. These curves are shown in figures 6 and 7.

$$\text{ETG, TTG} = a \cdot \text{MC}^2 + b \cdot \text{MC} + c \quad (1)$$

Development of an adjustment equation to convert the test MC to a specified MC was implemented by adjusting the 'c' coefficient so that the average equation would pass through the measured ETG or TTG value at the test MC. The ETG or TTG could then be calculated at other moisture levels. Adjustment of the 'c' coefficient was performed using equation 2.

Table 3. Coefficient of variation (%) of the slope values for MC vs. ETG and TTG data within specific MC intervals.

MC Interval	10% to 13% MC	13% to 15.5% MC
ETG	26.2	53.5
TTG	78.9	60.3

Table 4. Quadratic regression-model coefficients determined from regression using averaged grinding parameter data for each MC.

Parameter	a	B	C
ETG	5.1671	-49.481	3642.9
TTG	0.1611	-2.994	33.133

$$c' = c - (a \cdot \text{MC}_{\text{meas}}^2 + b \cdot \text{MC}_{\text{meas}} + c - \text{ETG}_{\text{meas}} \text{ or } \text{TTG}_{\text{meas}}) \quad (2)$$

where

$c'$  = adjusted 'c' coefficient

$\text{MC}_{\text{meas}}$  = MC at which grinding parameters were measured

$\text{TTG}_{\text{meas}}, \text{ETG}_{\text{meas}}$  = measured grinding parameter value

Corrected ETG and TTG values were then adjusted for MC using equation 3.

$$\text{ETG}_{\text{adj}}, \text{TTG}_{\text{adj}} = a \cdot \text{MC}_{\text{adj}}^2 + b \cdot \text{MC}_{\text{adj}} + c' \quad (3)$$

where

$\text{MC}_{\text{adj}}$  = MC to which grinding parameters were adjusted

$\text{ETG}_{\text{adj}}, \text{TTG}_{\text{adj}}$  = grinding parameter values adjusted

Figure 8 shows the effect of adjusting the c coefficient to fit a specific sample (hybrid 6) to TTG data at the 13% MC test value. The average curve is effectively shifted upward to coincide with the measured point at 13% MC. The adjusted curve can be seen to pass through the measured value at 15.5% MC but is considerably higher than the measured value at 10% MC.

Average and standard deviations of the error associated with adjusting grinding parameters are shown in table 5. These were calculated by fitting the adjustment regression curve to measured data at 10% MC and then determining the grinding parameter values at 13% MC from the adjusted equation. The average difference between actual data values at 10% and 13% MC is also shown. This is in effect the error incurred if values are not adjusted. The above procedure was repeated for other moisture levels as indicated in table 5. This effectively simulates the amount of error to expect using adjusted values. In all cases, adjustment to a common MC diminished the effect of MC on grinding data, but the average error remains reasonably high. Note that the same error results will occur when adjusted in the opposite direction, i.e. 10% MC adjusted to 13% MC will yield the same results as 13% MC adjusted to 10% MC, etc. These results can be shown by plotting values adjusted to a common MC versus measured values. Figures 9 and 10 show 10% and 15.5% ETG and TTG values adjusted to 13% MC versus actual ETG and TTG values at 13% MC. Coefficients of determination ( $r^2$ ) from linear regression between adjusted and measured values are shown in table 5.  $r^2$  values confirm that ETG values adjusted from 10% to 13% MC work reasonably well.

▲ Measured Hybrid 6 values    - - - Average Hybrid curve    — Adjusted average curve to Hybrid 6

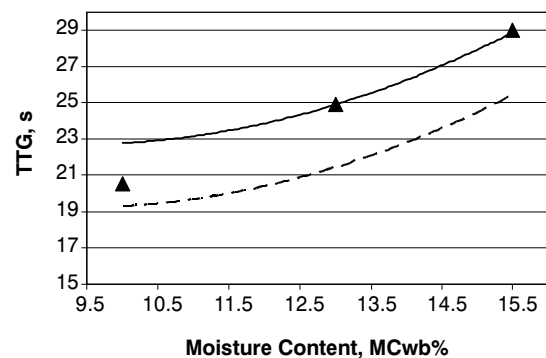


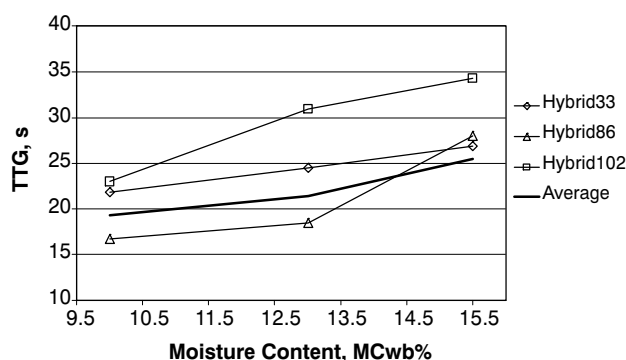
Figure 8. Graphical interpretation of adjusting the average curve to 13% MC for hybrid 6.

**Table 5. Error of ETG<sub>adj</sub> and TTG<sub>adj</sub> compared to non-adjusted values, ETG and TTG.**

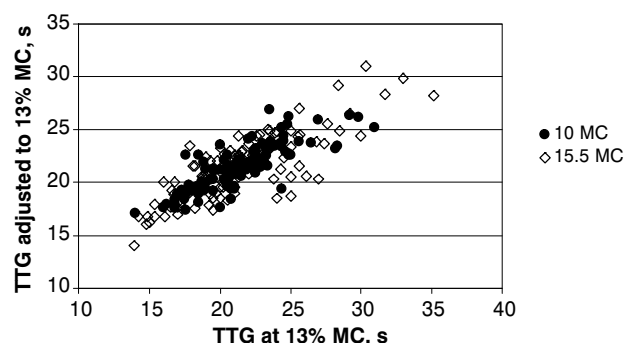
Analysis	Parameter	AVG Error	Standard Dev. Error	r <sup>2</sup>
10% MC, adjusted to 13% MC	TTG <sub>adj</sub>	1.29	1.07	0.66
	TTG	2.26	1.51	[a]
13% MC, adjusted to 15.5% MC	TTG <sub>adj</sub>	2.78	2.45	0.66
	TTG	4.03	2.36	[a]
10% MC, adjusted to 15.5% MC	TTG <sub>adj</sub>	2.26	2.01	[a]
	TTG	6.21	2.86	[a]
10% MC, adjusted to 13% MC	ETG <sub>adj</sub>	42.0	34.4	0.89
	ETG	280.0	54.5	[a]
13% MC, adjusted to 15.5% MC	ETG <sub>adj</sub>	91.7	92.9	0.44
	ETG	245.5	128.8	[a]
10% MC, adjusted to 15.5% MC	ETG <sub>adj</sub>	225.6	97.0	[a]
	ETG	452.5	144.3	[a]

[a] Regression analysis was not performed for this region.

Less error was observed for TTG data fit to 10% MC and adjusted to 13% MC. This contradicts conclusions from examining the cv of slopes but is attributed to the fact that the slope in the lower MC region is slightly smaller, and thus variations in MC do not affect TTG in this region as much as in higher MC regions. The MC spread, i.e. 10% to 15%, used in this study would be uncommonly large for most lab work if careful MC conditioning is practiced. This range, however, may be more common in receiving or processing operations. In any case, moisture should be known and adjusted made to obtain accurate comparisons between hybrids using grinding measurements.



**Figure 9. ETG values adjusted from 10% and 15.5% MC to 13% MC vs. measured 13% MC values.**



**Figure 10. TTG values adjusted from 10% and 15.5% MC to 13% MC vs. measured 13% MC values.**

## NIR PREDICTION OF GRINDING TIME AND ENERGY

Partial least-squares (PLS) regression was used to develop prediction models for ETG and TTG from spectra. Models were developed using GRAMS AI software (Thermo Galactic Industries, Salem, N.H.). The 20 spectra from each sample, whole kernel or ground, were averaged prior to analysis. Spectra were mean-centered, and cross-validation was performed with sequential removal of one spectrum. The spectral region was limited from 500 to 1700 nm due to noisy spectra below 500 nm. Reference values used in model development were ETG and TTG values determined at 13% MC. This approach allowed models to predict hardness at a common moisture level regardless of test moisture conditions. An alternative approach would have been to use actual ETG and TTG values and then adjust these using the moisture adjustment procedure developed. Considering the relative large error of the adjustment procedure, it was considered more appropriate to attempt predictions at a common moisture level. Statistics of the data and models are shown in table 6. Factor levels for the models were those suggested by the software and are based on the F-ratio which equals the predicted residual sum of squares (PRESS) at a specific factor level divided by the minimum PRESS value. The factor level of the model was set by determining the point at which adding a new factor to the model causes the F-test probability level to fall at or below 0.75. The F-ratio has been suggested by Haaland and Thomas (1988) as a better method for model development when the model will be used to predict future unknown samples. RPD is the ratio of the standard deviation of the reference data to the SECV. Williams (2001) suggested that RPD values of 2.5 to 3 were suitable for rough screening; 5 to 8 could be used for quality control; and 8 or higher was highly quantitative.

In general, predictive models had poor ability to measure either ETG or TTG. Models using flour spectra gave better results than those using kernel spectra. Spectra can be influenced substantially by particle size. Wheat hardness is determined using a particle-size index (PSI) (AACC, 2000) and has been established as having a primary effect on spectra when predicting hardness using near-infrared spectroscopy (Hruschka, 2001). Spectra should be similarly influenced by particle size for ground corn and may account for the small increase in NIR predictive ability for ground over whole-kernel samples. Regression coefficients for the ground-kernel PLS models (ETG and TTG) indicated that models were strongly influenced by wavelengths at 1680 nm. This region was previously used by Pomeranz et al. (1985) to

**Table 6. Statistics of PLS regression models developed to predict ETG and TTG.**

	Std.Dev.[a]	Min[a]	Max[a]	RPD[b]	R <sup>2</sup>	SECV[c]	Factors[d]
Whole Kernel							
ETG	158.9	3434.1	4124.9	1.44	0.51	110	16
TTG	3.12	14	31	1.25	0.33	2.49	14
Ground Kernel							
ETG	158.9	3434.1	4124.9	1.8	0.70	86	22
TTG	3.12	14	31	1.45	0.53	2.14	17

[a] Standard deviation of reference data (joules or s).

[b] Ratio of standard deviation of reference to SECV.

[c] Standard error of cross-validation (joules or s).

[d] Number of factors used in prediction.

discriminate hardness. Wavelengths at 860 nm, in contrast to Robutti (1995), were not highly weighted in any of the models.

## CONCLUSIONS

Large differences in grinding speed can cause differences in ETG and TTG but should be easy to control by limiting speed difference between tests by using similar speed control used in this work. The coefficient of variation from replicated tests indicated that the repeatability of ETG to TTG are similar.

ETG and TTG are strongly affected by MC. Corn hybrid grinding response to MC is more predictable for ETG in the region of 10% to 13% MC, compared to the higher MC region and to TTG -MC behavior. Adjustment of ETG and TTG data to a common MC can be useful in establishing good comparative grinding parameters between hybrids but there are some shortcomings due to the variability of grinding parameters by hybrids. Ultimately, the best results can be obtained by using adjusted ETG data and limiting the sample MC range to 10% to 13% MC. Prediction of grinding parameters using NIR spectroscopy does not seem feasible from the results of this study.

## REFERENCES

- AACC. 2000. Approved methods of the AACC, Method 55-30 and 44-15A. St. Paul, Minn.: AACC.
- ASABE Standards. 2006. S352.2. Moisture measurement - unground grain and seeds. St. Joseph, Mich.: ASABE.
- Dorsey-Redding, C., C. R. Hurburgh, L. A. Johnson, and S. R. Fox. 1990. Adjustment of maize quality data for moisture content. *Cereal Chem.* 67(3): 292-295.
- Haaland, D. M., and E. V. Thomas. 1988. Partial least-squares methods for spectral analysis. 1. Relations to other quantitative calibration methods and the extraction of qualitative information. *Analytical Chemistry* 60: 1193-1202.
- Hruschka, W. R. 2001. Data analysis: wavelength selection methods. In *Near-Infrared Technology in the Agricultural and Food Industries*, 2nd ed., eds. P. C. Williams and K. Norris. St. Paul, Minn.: AACC.
- Kirleis, A. W., K. D. Crosby, and T. L. Housley. 1984. A method for quantitatively measuring vitreous endosperm area in sectioned grain sorghum. *Cereal Chem.* 61(6): 556-558.
- Lawton, J. W., and J. M. Faubion. 1989. Measuring kernel hardness using the tangential abrasive dehulling device. *Cereal Chem.* 66(6): 519-524.
- Li, P. X., A. K. Hardacre, O. H. Campanella, and K. J. Kirkpatrick. 1996. Determination of endosperm characteristics of 38 corn hybrids using the Stenvert hardness test. *Cereal Chem.* 73(4): 466-471.
- Liao, K., J. F. Reid, M. R. Paulsen, and E. E. Shaw. 1991. Corn kernel hardness classification by color segmentation. ASAE Paper No. 913504. St. Joseph, Mich.: ASAE.
- Martin, C. R., R. Rousser, and D. L. Brabec. 1993. Development of a single-kernel wheat characterization system. *Transactions of the ASAE* 36(5): 1399-1404.
- Paulsen, M. R., S. A. Watson, M. and Singh. 2003. Measurement and maintenance of corn quality. In *Corn Chemistry*, eds. P. White and L. Johnson, 193-195. St. Paul, Minn.: AACC.
- Pomeranz Y., C. R. Martin, D. D. Traylor, and F. S. Lai. 1984. Corn hardness determination. *Cereal Chem.* 61(2): 147-150.
- Pomeranz, Y., Z. Czuchajowska, C. R. Martin, and F. S. Lai. 1985. Determination of corn hardness by the Stenvert Hardness tester. *Cereal Chem.* 62(2): 108-112.
- Pratt, R. C., J. W. Paulis, K. Miller, T. Nelsen, and J. A. Bietz. 1995. Association of zein classes with maize kernel hardness. *Cereal Chem.* 72(2): 162-167.
- Robutti, J. L. 1995. Maize kernel hardness estimation in breeding by near-infrared transmission analysis. *Cereal Chem.* 72(6): 632-636.
- Stenvert, N. L. 1974. Grinding resistance, a simple measure of wheat hardness. *Flour Anim. Feed Milling* 12: 24.
- Tran, T. L. J. M. deMan, and V. F. Rasper. 1981. Measurement of corn kernel hardness. *Canadian Inst Food Sci. and Tech.* 14(1): 42-48.
- Williams, P. C. 2001. Implementation of near-infrared technology. In *Near-Infrared Technology in the Agricultural and Food Industries*, 2nd ed., eds. P. C. Williams and K. Norris. St. Paul, Minn.: AACC.

